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DESIGN PARAMETERS AND

COLOR CRT DISPLAY DESIGN

by

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This report considers a number of the principal variables worthy of inclusion in any attempt to apply color coding to CRT display design.

INTRODUCTION

The sensing function in man is accomplished by means of a complex arrangement of specialized sensory mechanisms called receptors. Receptors are classified according to the type of physical energy to which they are sensitive. As such, man possesses photic receptors, mechanical receptors, thermal receptors and chemical receptors. Receptors represent the interface between the external environment and transmitting and processing subsystems of the human organism.

Receptor mechanisms function to transform various forms of physical energy into electrochemical energy suitable for transmission by the nervous system, and code available information for eventual processing and decision making.

Visual Subsystem

The receptor mechanism sensitive to photic energy is the visual subsystem. The peripheral organ of vision consists of the eye. Through its physical structure the eye is capable of focusing light emitted from external objects to light sensitive area existing within the eye itself. The visible spectrum of electromagnetic radiation is roughly limited to wavelengths between 380 and 800 millimicrons with a frequency range of approximately 7×10^{14} to 4×10^{14} Hz (Grossman, 1967). The eye does not respond to energy greater or less than these values unless intensity is sufficient to produce injury (Heimstra and

Ellingstad, 1972). Color sensation results from stimulation of the light sensitive area of the eye (retina) by successive wavelengths of the visible spectrum.

Structure of the eye

Figure 1 presents an illustration of eye and points out some of the major structures involved in the visual process.

Components of eye

Cornea. The cornea represents the outer most transparent layer of the eye. It is devoid of blood vessels and is extremely sensitive to noxious stimuli. It serves to bend light entering the eye to form the image transmitted to the receptors located at the rear of the structure (retina).

Iris and Pupil. The iris is responsible for regulating the amount of light entering the eye and subsequently falling on the photosensitive retina. It represents the pigmented portion which gives color to the eyes.

The pupil is the aperture in the center of the eye which dilates or contracts in response to stimulus intensity. Pupillary contraction has been observed when an individual views stimulii considered distasteful, suggesting a psychological component to pupillary response.

Lens. The lens consists of a series of concentric layers of tissue. It is suspended from the ciliary muscle which provides the mechanism for modification of lens shape, enabling further focusing of stimulation. Shape modification process is known as accommodation and is responsible for altering the radius of curvature necessary for distance and near vision. The ability of the lens to modify its shape is significantly influenced by age in that lens elasticity decreases with advancing age.

Acqueous Humor. Acqueous humor is located in front of and to the sides of the lens. It is a free flowing, clear material that is constantly being formed and reabsorbed. This formation-reabsorption process serves to regulate total volume and pressure of intraocular fluid.

Retina. Retina constitutes the most complex aspect of the visual system. It consists of several layers which are made up of receptors as well as highly complex networks of nerve cells responsible for transmitting stimulation to the central nervous system.

Receptors. The outermost layer of the retina consists of pigmented epithelium which serves to absorb light and help prevent light scattering and blurring of the retinal image.

Below the outermost layer are actual receptors which are tightly packed together at the rear of the eye (Butter, 1968).

Visual receptors are of two types and as a result of their shape are commonly called rods and cones. In addition to shape these two types of receptor mechanisms are quite different in terms of function.

(a) Rods

Rods are distributed throughout the retina with highest concentrations in the periphery. They are sensitive to low levels of illumination and respond in such a fashion as to lead to a visual experience of shades of gray rather than color. Rod functions are known as scotopic vision.

(b) Cones

Cones function under higher levels of illumination than rods, and are most important in relation to the eye's ability to see fine detail and color. They are concentrated in the center of the retina with highest concentration at the fovea. Cone vision is known as photopic.

Fovea. Near the center of the retina is a slight depression known as the fovea. Fovea consists of a minute area occupying approximately 1 square millimeter (Guyton, 1970). It is the region particularly suited for detailed vision and is composed entirely of cones. The structure of cones in the fovea differ significantly from cones found in the periphery of the retina.

Further, unlike other areas of the retina, ganglion cells, plexiform layers, etc., are displaced to one side as opposed to resting on top of the receptors themselves. This feature allows light to pass directly to the receptors as opposed to being filtered through several layers of retina prior to striking the cones. This aspect of foveal structure combined with the one-to-one ratio of cones to neurons in the fovea probably provides much of the basis for increased sensitivity of foveal vision. Figure 2 indicates relative acuity of regions of the retina.

Vitreous Humor. Vitreous humor is the second type of intraocular fluid which aids in maintenance of sufficient pressure in the eye to maintain its spherical shape. Vitreous humor lies between the lens and the retina. Rather than a free flowing liquid, vitreous humor in a gelatinous mass interlaced with a fine fibrillar network. Further, vitreous humor is essentially an inert mass with little turnover of fluid.

Optic Nerve. Figure 2 shows that at a point approximately 15 degrees from the fovea on the nasal side there is a "blind spot." This is the point where ganglion cells exit the eye and the optic nerve and blood vessels enter the eye. As a result this area is devoid of sensors and represents a blind area in the visual field.

Photochemistry

Both types of visual receptors contain chemicals which decompose upon exposure to light. Chemical changes which take place aid in translating physical energy into nerve impulses. The process and chemicals involved is much better understood for retinal rods than cones. However, it is believed that cones contain pigmented chemical composition similar to rods and that photochemical principles applicable to rod vision are generally applicable to cone vision (Ruch, 1966).

In the case of rods, that portion which extends into the pigmented layer of the retina contains about 40 percent concentration of a light sensitive pigment called rhodopsin (Guyton, 1970). When light strikes the outer segment of the rods it is absorbed by light sensitive photochemicals which in turn is "bleached" or broken down into retinene, a derivative of Vitamin A, and opsin, a protein (Butter, 1968). During the decomposition process, a receptor potential is generated which excites nerve impulses at the neuron which synapse with receptors. It has been hypothesized that mechanisms by which decomposition initiates nerve impulses involves a splitting away from retinene by a substance known as scotopsin exposing several sulfahydryl bonds which momentarily ionize scotopsin. The ionic change creates a local electrical potential that acts directly on rod membranes thereby creating a receptor potential (Guyton, 1970).

Following decomposition of rhodopsin, the two substances, retinene and scotopsin, are automatically reformed into rhodopsin. Reformative processes take place spontaneously as a result of a large amount of free energy stored in retinene and resulting from original exposure to light which caused initial decomposition.

Color Photochemistry.

It was suggested above that photochemistry of cones is not as well understood as photochemistry of rod vision. As cones are responsible for color vision, several questions relative to color photochemistry presently exist. Guyton (1970) however, has postulated that the primary difference between rod and cone photochemistry involves the protein portion of cones (photopsin) and rods (scotopsin). Guyton (1970) has suggested that color sensitive pigments are a combination of retinene and photopsin There are three different color pigments present in different cones making cones selectively sensitive to red, green and blue. Absorption characteristics in the three types of cones suggest peak absorption at 430 (red), 540 (green) and 575 (blue) millimicrons. Figure 3 presents absorption curves for the three color pigments in color sensitive cones.

Visual Processes/Perception

The subject of visual perception can be conveniently divided into three parts: color vision, brightness vision and spatial vision (Morgan and Stellar, 1950). As the concern of the present effort is on color vision, with particular application to color in the design of CRT/electronic displays, emphasis will be placed on color vision. However, it should be noted that it is not possible to consider any one visual process to the exclusion of the others. The degree of interaction between various visual functions renders consideration of all visual functions necessary in a total and comprehensive examination of visual display design parameters. Therefore, the reader is cautioned that consideration of all aspects of visual perception is essential in any overall visual display design study.

Color Perception and Display Design

Morgan and Stellar (1950) suggested at the time of their writing that processes underlying color vision were a mystery. Some progress has been made since their original statement, however, it is still safe to conclude that color vision remains an enigma today. This is particularly true of the use of color in CRT/electronic display design.

Psychological Components in Color Vision.

An important aspect of color perception involves the presence of psychological parameters. Color vision has been considered to consist of three psychological aspects: hue, saturation and brightness (Roth and Finkelstein, 1968). Hue refers to that aspect of visual perception we normally think of as "color" (e.g., red, green, blue, etc.) (Cornsweet, 1970). The physical property most closely related to hue is wavelength.

Saturation refers to purity of hue. It is that aspect of color most strongly influenced by the addition of white light. Roth and Finkelstein (1968) defined saturation as the degree to which a sensation of hue differs from gray with the same level of brightness (intensity). For example, a 100% saturated red (spectrum red) becomes more "pink" with the addition of white light. However, in terms of hue it is still red, only a red of decreased saturation.

The third psychological component of color perception involves brightness. Brightness is related to intensity or amount of luminous flux reaching the eye from a stimulus. Generally a higher intensity light source will appear more brightly colored, while a low intensity will appear more dull.

In addition to the above so-called psychological components, consideration must be given to the human dependent parameter of contrast. While brightness is essentially a measure of light intensity of a signal, contrast is the relative brightness of signal over background brightness. It has been suggested that

reading ease is directly related to contrast (NASA SP-5049, 1968). Therefore, contrast may be viewed as related to visual acuity and any reduction in contrast can be expected to reduce visual acuity o the ability to determine detail (Roth and Finkelstein, 1968).

It should be mentioned that there are two "types" of contrast: brightness and color. Brightness contrast appears to be a far more important variable in visual performance in that the greatest color contrast possible produces visual acuity roughly equivalent to the acuity produced by a brightness contrast of 35% (Roth and Finkelstein, 1968).

Color Vision Deficiencies

Any consideration of color in display design must be aware of the problem of color vision deficiencies in the potential user population. Roth and Finkelstein (1968), Ruch (1966) and Allen (1970) have all suggested that a rather large segment of the male population (6 to 8%) and much smaller segment of the female population (.05%) possess significant color vision deficiencies. Total color blindness has been estimated to occur in .003% of the population (Roth and Finkelstein, 1968). Given this rather large segment of the population with color vision deficiencies, coupled with the fact that color vision ability is rarely used as a factor in operator selection, consideration must be given to color selection in terms of known color vision deficiencies.

Classification of Color Deficiencies

Conventional classification of color deficiencies is as follows:

(1) Trichromats

(2) Dichromats

(3) Monochromats

Labels attached to various classifications indicate the number of primary colors (red, green, blue) needed in order to match all colors in the visible spectrum. That is, trichromats require all three primary colors, as do normals, however, the color deficient trichromat differs from "normal" in that he is deficient in one of the three photochemical substances necessary for "normal" color sensitivity (Heimstra and Ellingstad, 1972). For example, a green deficient trichromat (deuteranomalous) would require considerably more green in a red-green mixture before he could recognize yellow. A red defective (protoanomalous) would require more red in a red-green mixture before he could experience yellow.

Dichromatism is characterized as a form of color blindness and results from the complete absence of one of the three photosensitive pigments. Dichromats can match the spectrum (as they see it) with only two primary colors, a green and blue for protanope and red and blue for deuteranope (Ruch, 1966).

Monochromats are characterized by a complete absence of at least two of the photosensitive pigments. Hurvich (1973) has suggested one-variable monochromats can be characterized

perceptually in terms of variation along the brightness dimension only, and a luminance control is adequate to generate color matches among stimuli of different wavelengths.

The point of interest in various color deficiencies is the potential they possess for error generation in operator performance. As suggested earlier color vision is infrequently used as a variable in selection of potential operations combined with the fact present methods for color vision determination are far from accurate suggests that color selection for coding should be limited to colors recognizable by color deficient individuals.

Roth and Finkelstein (1966) have suggested that only aviation red, green and blue be used in display panels if color defective individuals are potential operators. The designation of "aviation" imposes a significant problem in CRT/electronic display media in terms of "state of the art" and in many cases may not be possible. However, the authors indicate that the aviation designation is critical if confusion is to be avoided by color deficient individuals.

In summary, the primary objective of any display is to provide information relative to a situation which is occurring or has occurred to a human operator (Murrell, 1969). Considerable research has been devoted to the determination of the most effective and efficient manner in which to display desired and necessary information. The use of color has been examined and is currently surrounded with controversy.

Two basic uses of color coding have been explored: coding and natural color representation (Wagner, 1977). In the case of color coding, color is substituted for some other coding modality (e.g. shape). In the case of using color as a natural color representation, color is employed as a means of presenting realistic or natural imagery. In terms of research, color coding has been the recipient of far more effort. What is to follow will concentrate on reviewing colors as a coding modality in display design.

<u>Variables for Consideration in Evaluating Color Use</u>

As in any display design question, it is necessary that careful consideration be given a number of subject areas relative to the use of color. At a minimum it is necessary to examine the following:

(1) Objective of display

(2) Operator task(s)

(3) Operator capabilities and limitations (e.g. color deficiency)

(4) Operator workload

(5) Work environment (e.g. ambient illumination)

(6) Colors available with display system hardware

(7) Conventional meaning of colors used (e.g. red-hazard)

(8) Use to be made of color (e.g. what function will color serve)

(9) Coding combinations (e.g. color + alphanumerics).

Few studies exist however, which actually consider multiples of the above in a specific application. Most studies available in the literature have concentrated on a comparison between color as a coding modality versus some other method of codi (e.g. shapes). Christ (1975) has indicated there are no data available for making valid comparisons, and many available evaluations have been severely restrictive in conditions under which obtained. What is apparent from available research is that a good display in one situation and/or application may be a poor display in a dissimilar situation and/or application.

General Consideration

General considerations to follow are based on the use of color in CRT/electronic display designs as an aid to information transfer in terms of an additional level of decision making assistance. Concentration remains on the use of color as a coding modality.

Objective/Task

Wagner (1977), states that color is beneficial in search and locate type tasks, but that other coding modalities appear to be more effective in identification, etc. tasks. Christ (1975) observed that in an identification task (i.e., task is one of identifying a specific feature of a target stimulus) colors can be identified more accurately than size or shape, but are identified with less accuracy than alphanumerics.

Christ (1975) reported that color can be 176% better than size, 32% better than brightness and 202% better than shape. However, when compared with alphanumerics, color was found to be 48% less accurate.

Hitt (1961) investigated the effectiveness of five coding methods including color, shape, configuration and number in terms of identifying counting, verifying and comparing. His observations suggested colors were better for locating while numbers were better for identifying. Similar conclusions were drawn by Cook (1974) in a review of color coding literature. Literature reviewed indicated numerics were superior for identification and color best for search and attention getting. Christner and Ray (1961), investigated the effectiveness of various target-background coding combinations. Target codes included 8 colors, 8 number and 8 shapes. Background codes included five shades of gray as brightness codes, five patterns, white, gray and five colors. Combinations were studied under target numbers, high and low densities and coding dimensions. Their results were similar to previously cited authors in that numbers resulted in better performance on identification and colors better for search performance.

In a very comprehensive review of existing literature, Teichner, et al. (1977) reported on 132 experimental comparisons of performance on identification type tasks and observed that color might be better than size or brightness but no better

and perhaps poorer than other coding dimensions. In 59 experimenta comparisons of search type tasks, color was consistently better.

Therefore, based on available literature it would certainly appear color may be beneficial in tasks involving searching for targets and that this superiority would seem to be maintained over a wide range of conditions and densities. In tasks involving identification the literature would suggest that color is inferior to certain other coding modulations (e.g., alphanumerics) and should be avoided.

In summary, tasks characteristic should dictate the use of color with use being restricted to general attention getting situations. Its value would appear to be to facilitate "chunking" in the Miller (1956) sense of the term.

Operator Capabilities and Limitations

The limitation(s) of color vision deficiency were specifically addressed in an earlier discussion. Additional coverage will be devoted here, however, with an orientation toward performance and causes as opposed to the specific phenomena.

Allen (1970) has postulated that color vision defects may be either acquired or inherited. Acquired deficiencies accompany diseases or substances which affect the retina, visual cortex and/or nerve pathways.

Diseases which can influence color vision include: pernicious anemia, vitamin deficiency, diabetics, optic neuritis, etc. More importantly, toxic amblyopia has the potential for

degrading color (Allen 1970). Causes of toxic amblyopia include carbon disulfide, lead, some antibiotics and tobacco.

Inherited defects are primarily the result of genetic causes and reside in defects in photopigment. These defects are considered to account for the majority of color vision deficiencies.

Allen (1970) has indicated that the socalled "color normal" individual is only "normal" under special conditions. Allen has suggested that parafoveal vision resembles deuteranomaly (weak red-green), intermediate peripheral vision deuteranopia (little if any red-green) and extreme peripheral resembles monochromatism (light-dark). Further, during short or repetitive flashes of light, normal color sensations may not occur at all or may develop in a very "abnormal" fashion. Sensations will be dependent upon color of stimulus, frequency rate, light/dark interval and surround. Color preception abnormalities may also occur following pre-adaptation to a specific color or exposure to a color with an intensive colored background as surround.

Therefore, color vision deficiencies may represent a potential degrading influence in human performance relevant to color coding in display design. Potential for degradation is not well understood, but available evidence justifies consideration be given to performance limitation.

Thresholds and Visual Acuity

Krebs (1977) has stated that operator ability to distinguish fine detail is a function of symbol and background color with greatest sensitivity at the red end of the spectrum. It would appear, however, that intensity or luminance is of more importance than color contrast. Roth and Finkelstein (1968) have stated that the highest possible color contrast will produce visual acuity roughly equivalent to 35% brightness contrast. As such visual acuity will be improved much more by increasing brightness than color contrast. At photopic luminance levels (high intensity) color appears to influence visual threshold in various ways depending upon other factors present in the situation (Overington, 1976). First, if symbol and background are of the same color, but non-neutral, there can be a slight effect on visual threshold as a result of a shift in spectral balance. In situations where symbol and background are of a different color (hue) there will be a thresho associated with a hue when luminosities are equal. Maximum sensitivi seems to be in yellow/orange and blue/green with reduced sensitivity in green and poor sensitivity at extreme blue and red.

Last, in situations where color and intensity are different, overall contrast can be defined as the root mean square of intensity and chromaticity contrast. That is:

$$C = \sqrt{C_L^2 + C_c^2}$$

where

C = contrast

C_L = luminosity contrast

C_c = chromaticity contrast

In short, visual acuity with color would appear to be dependent upon a number of factors including color of symbol (target) and background (i.e. contrast), luminance, target size and shape, information displayed, etc. The question of condition which will produce greatest ability in terms of discriminating fine detail is unclear and demands that attention be paid to each specific application. About the only concrete conclusion is that blue should be avoided as the fovea is blue blind (Krebs, 1977).

Ambient Illumination

High ambient illumination will tend to reduce symbol to background contrast and as such can be expected to degrade overall performance (Krebs, 1977). Sensitivity increases with adaptation to darkness, and photosensitive substances increases in volume under dark adapted conditions. Roth and Finkelstein (1968) has suggested the following as factors related to sensitivity:

(1) duration of luminance

(2) average pre-exposure luminance

(3) size, shape, contrast and viewing time

(4) color of pre-exposure light

(5) region of retina stimulated

(6) physiological status of operator.

Krebs (1977) has reported that at high ambient illumination levels response time is fastest at both red and blue ends of the spectrum with slower times reported for yellow to yellow/orange segment of the spectrum. Ellis, et al. (1975) have indicated that in order for green to be equally visible to red under conditions of high ambient illumination it must be three times the luminance. Therefore if ambient illumination conditions are high the recommendation would be to use red as the coding color.

On the other hand, performance is also likely to be degraded in situations involving low levels of ambient illumination. In a dark environment it will be necessary to reduce symbol luminance to a low level in order to maintain dark adaptation. In such situations it is possible to reduce symbol luminance to a level that prevents operators from perceiving color thereby rendering color coding useless.

The possibility of glare represents a further condition that may be present under conditions of high ambient illumination. If illumination is excessive it tends to interfere with visual performance by reducing contrast thereby reducing visibility and/or readibility. Glare, regardless if reflected or specular, can also cause discomfort which can induce subjective fatigue resulting in performance impairment.

Symbol Size with Color Displays

Symbol size, visual acuity and resolution can be considered as related variables. Resolution is the measure of discrimination of fine detail and is necessarily dependent upon visual acuity as well as total display resolution. Display resolution is in turn dependent upon element or symbol size bluntness of "pen" drawing the displayed object, the display itself (e.g. contrast, luminance, etc.), and types of information displayed (NASA, 1968). Any attmept to consider symbol size must include consideration of symbol and color perception and the fact that different requirements exit for each (Krebs, 1977). That is, it is possible to "see" and identify a symbol without the symbol being large enough to enable color recognition. Krebs (1977), has stated that for adequate color perception symbol size varies from 21 to 45 minutes of arc, depending upon number of colors involved (see Figure 4).

The following electronic/CRT display requirements, in terms of symbol size, have been suggested by Krebs (1977):

(1) 21 minutes of arc-minimum

(2) As numbers of colors used increases minutes of arc increase to 45.

(3) Stoke width--2 min. of arc at a minimum.

(4) Line width for graphs--4 min of arc at a minimum.

(5) Symbol aspect ratio--5:7 or 2:3.

Display Locations

Color vision is apparently significantly reduced in the periphery. In fact, the eye is sensitive to color in a very small part of the total field of view ($\pm$ 1 degree)(Krebs, 1977). Therefore, use of color coding in displays which lie outside normal line of sight is questionable. In particular, peripheral display must restrict the use of red as the periphery is very insensitive to red.

Color Selection

Given that the decision has been made to use color, the next question is what colors and how many? As in all situations involving color a number of considerations enter into the determination. First, there is general agreement that the number of codes employed should not exceed four (Krebs, 1977; Ruch 1968; Wagner, 1977, etc.). With extensive training it may be possible for observers to identify as high as 50 colors (Hanes and Rhoades, 1959). However, in the applied sense, particularly if absolute identification is required, color use should not exceed 4. Obviously, the number of colors selected will depend upon the nature of the task, display limitations (technology) ambient illumination, operator workload, signal criticality, etc. But as a "rule of thumb" three or four colors should be considered as the upper limit.

Which Colors to Use

The following criteria have been suggested by Krebs (1977) in color selection:

(1) Maximize wavelength separation

(2) Maximize color contrast

(3) Visibility in specific application

(4) Maintain conventional meaning

(5) Legibility and reading ease

(6) Use highly saturated colors.

Baker and Grether (1954) have indicated the ten colors listed in Table 1 are highly identifiable under good viewing conditions. Cook (1974) has suggested a six color set for use in color coding (see Table II).

Color sets suggested above suffer from a common problem in that recommendations are frequently based on laboratory tests and/or involve the capability of a subject to accurately identify a color under good viewing conditions. In the "real world" the task required seldom consists of mere color identifications, rather it is frequently considerably more complex than simply being able to identify a specific color. The question of "blue blindness" has been suggested by Krebs (1977) as an example of the difference between color identification under good viewing conditions and the use of color in a true information transfer situation. That is, the fovea is essentially blue blind and in addition, is the area most sensitive in fine discriminations. Therefore, a subject may be capable of identifying

TABLE I. Identifiable Colors Under Good Viewing Conditions (From Baker and Grether, 1954).

Color	Wavelength (nanometers)
Violet	420
Blue	476
Greenish/Blue	494
Bluish/Green	504
Green	515
Yellow/Green	556
Yellow	582
Orange	596
Orange/Red	610
Red	642

TABLE II. Six Color Set for Use in Color Coding (from Cook, 1974).

Color	Wavelength (nanometers)
Purple	430
Blue	476
Green	515
Yellow	582
Orange	610

color, but be unable to make fine discrimination. In fact, Krebs (1977) has recommended blue symbols to be at least 1 degree or more larger than other colors in color coding symbols.

In recommending colors to be employed in symbol color coding it would appear that red, white and yellow are superior to either blue or green. These conclusions are based on experimental results produced by Meister and Sullivan (1969) and Rizy (1965). Blue and green should probably be limited to coding zones or if unavoidable lines. The use of blue or green in coding alphanumerics should probably be avoided.

One further point in considering color coding involves the question of population stereotypes. Over an extended period of use the colors red, green and yellow particularly have come to be associated with warning, safe and caution respectively. Any use of these colors should consider these associated meanings and make every attempt to incorporate them into any design effort. Violation of color code convention is inviting error and subsequent performance degradation.

In summary, the following recommendations for using color in CRT/electronics display design should be adhered to whenever possible (Krebs, 1977):

(1) Maximum of four colors.

(2) Alphanumeric should be coded with red, white and yellow.

(3) Blue should be limited to use involving large areas.

(4) White should be used to code peripheral signals.

(5) If applicable follow conventional use of color codes.

Color Coding and Performance

The real question to be answered is whether or not color coding of electronic/CRT display will enhance performance sufficiently to be cost effective. As in all areas of research on color coding, considerable controversy surrounds the issue of color coding in CRT type displays in terms of potential enhancement or degradation of operator performance. Available research does suggest that in certain situations and tasks, color can serve to improve performance and may be superior to other coding modalities (e.g. alphanumeric, symbols, etc.). Oda (1977) for example has concluded that computer aided color coded information could reduce reaction time and errors when applied to designs of ASW tactical displays. Markoff (1972) examined resolution, target size, ambient illumination and chroma in a target recognition type task. Colored targets were recognized faster and fewer errors occurred than with black and white. Hitt (1961) provided results suggesting color coding had advantages over numbers and symbols in a task of locating targets in noise. Similar results on a similar were observed by Christner and Ray (1961). Burdick et al., (1965) in a review of the literature emphasized cost effectiveness. They concluded color was probably cost effective in some tasks (i.e. search and locate).

On the other hand there exists considerable evidence to suggest color of no benefit and possibly a detriment in certain types of tasks in specific situations. Teichner, et al. (1977) in a series of experiments including various tasks concluded

color coding was of little decrement or benefit in terms of performance. Fowler and Jones (1972) investigated target acquisition with color and black and white TV. Their observation suggested no benefit of color on detection or range recognition. Christ and Corso (1975) conducted a series of 10 experiments comparing color codes to letters, geometric shapes and digits. Their findings indicated color was not superior in the tasks investigated. Geometric shape coding was comparable in most cases investigated.

Additional work has been conducted on colors as a totally or partially redundant feature (i.e. color used in combinations with a second coding modality). In a totally redundant situation, only one of the coding modalities is necessary for identification. If the two coding functions are only partially correlated, partial redundancy is said to exist.

Kanarich and Peterson (1971) examined color or numbers versus redundant presentation and found no benefit to performance with redundancy. Saenz and Riche (1974) investigated the effects of shape, colors and redundant shape-color codes on a search and detection task. Color and redundant codes were superior to shape in terms of performance. However, they did not observe a significant enhancement or degradation is a result of redundancy.

Krebs (1977) has suggested the use of total redundancy to (a) improve symbol visibility and (b) improve symbol discriminability. Partial redundancy should be used to categorize information of more than one level of specficity.

Therefore, it does not appear possible to say color will definitely degrade or enhance performance in any specific situation or task. It does appear that color coding has some advantages in search type tasks. There is little question that observers prefer color coded vs monochromatic displays. This psychological factor cannot be disregarded as an element of consideration. Particularly when one considers subjective fatigue and motivation in terms of performance.

In general, we can summarize the variables of interest in color display research as follows:

(1) Color itself (wavelength)

(2) color contrast

(3) number of colors displayed

(4) Brightness contrast

(5) Color vision deficiency

(6) Display density

(7) Exposure time

(8) Nature of task

(9) Operator workload

(10) Population stereotype

(11) Coding combination (redundancy)

(12) Psychological aspect of presenting information in color as opposed to black and white.

(13) Display position.

The present "state of the art" does not allow for a definite statement regarding the use of color in CRT display design. Performance does not appear to be significantly influenced under most situations with the use of color. Color displays seem to be most advantageous in search and locating type tasks. Although available data does not make a particularly strong case for color with the search and locate task. One significant limitation to color use is the small number of coding dimensions available (4 at maximum). Therefore, any attempt to apply color coding must necessarily be limited to information possessing involving a maximum of four conditions. If used, it would appear color should be used in a categorization or classification scheme quite small in scope.

The question of color use is not well documented. Based on available research the question of cost effectiveness must be considered. Particularly in view of the rather large cost of producing color displays as compared to black and white. Before any statement relative to color coding in CRT display design can be made additional work is necessary and may be dependent upon technological outcomes in color display design.

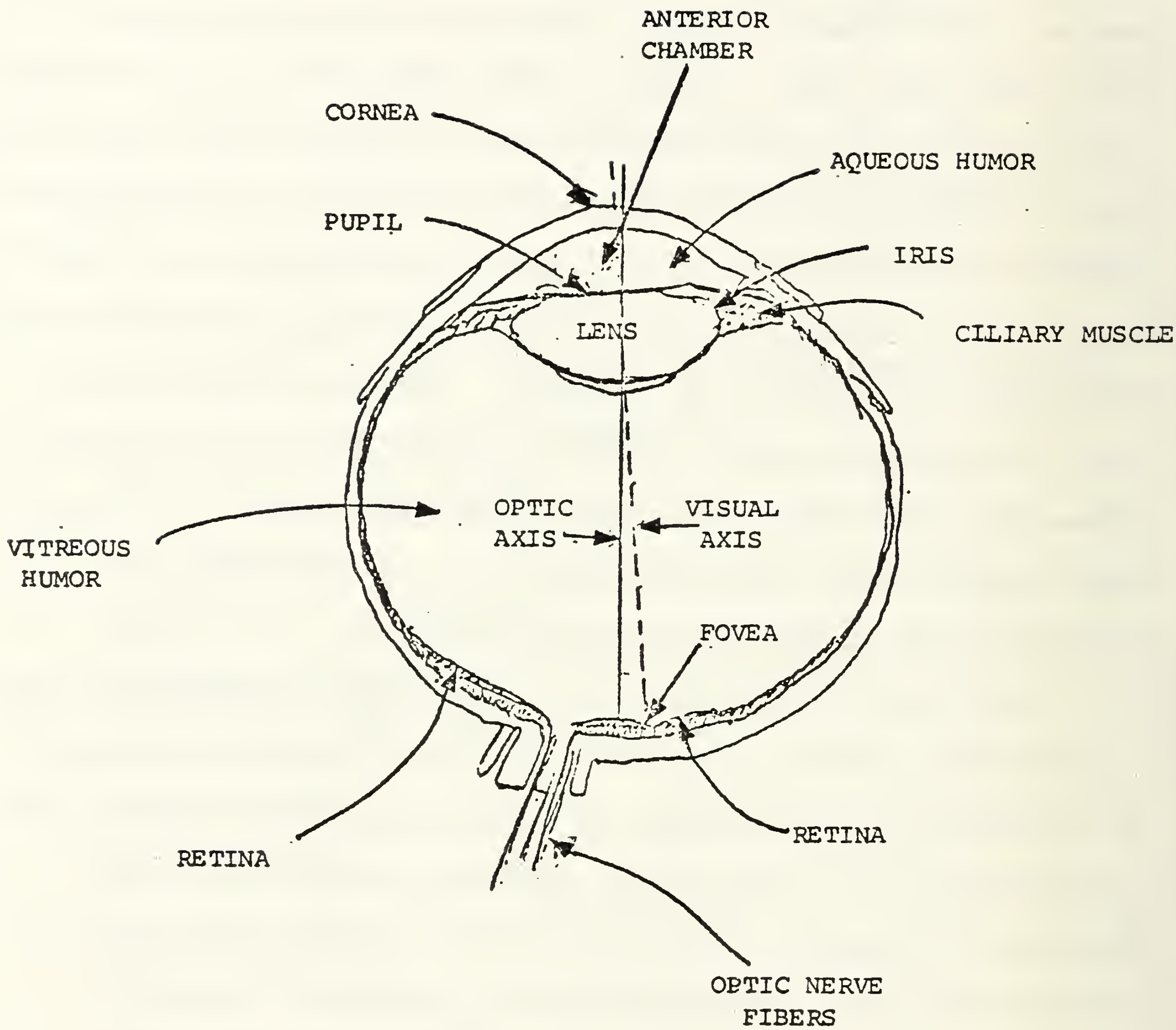

FIGURE 1. Gross Structure of Human Eye (from Ruch and Patton, 1966).

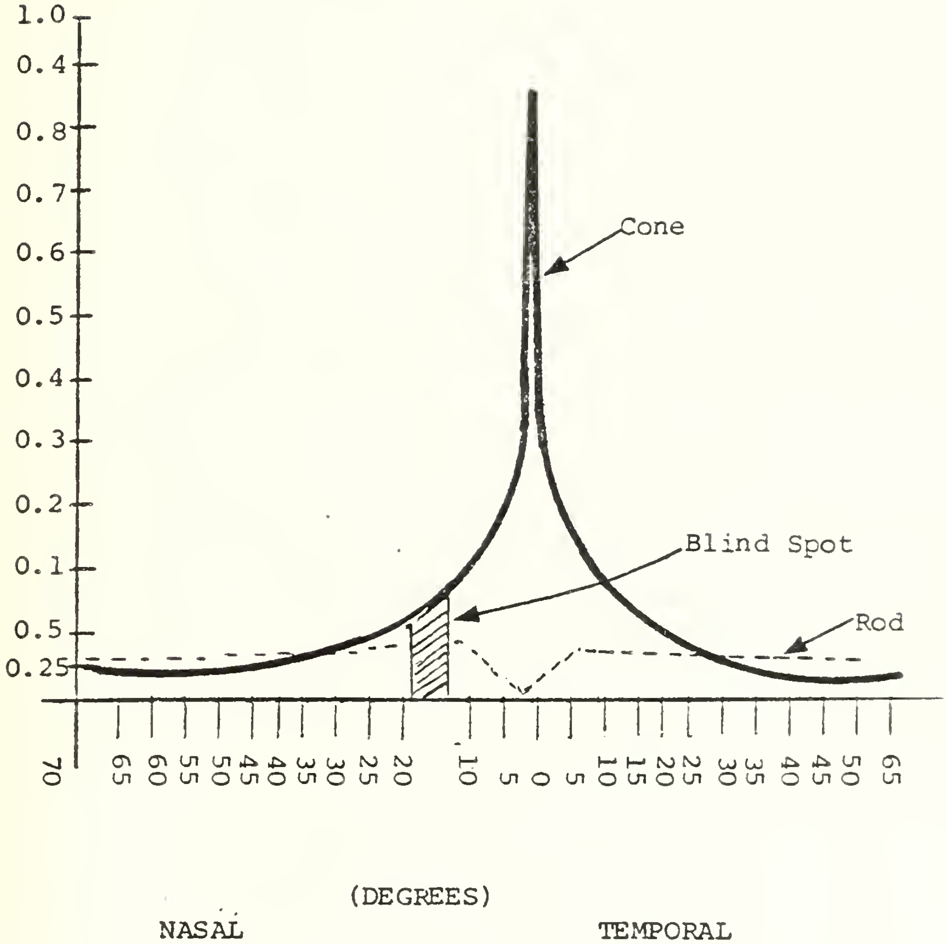

FIGURE 2. Curve of Relative Acuity of Vision in Central and Peripheral Fields of Retina (after Ruch Patton, 1966).

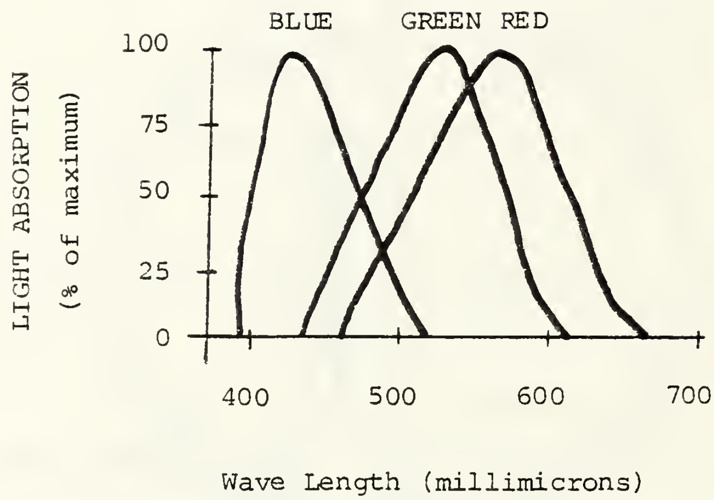

FIGURE 3. Light Absorption by Three Pigments in Color Receptive Cones (after Guyton, 1970).

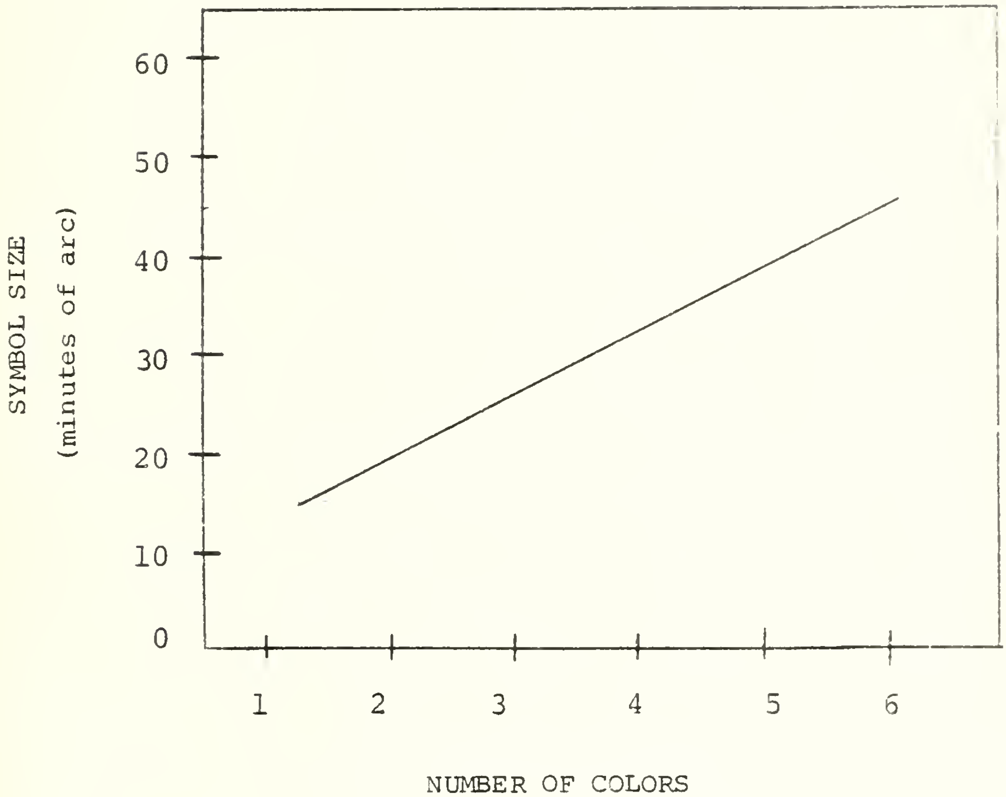

FIGURE 4. Symbol size as a function of number of colors displayed. (Perception of color adversely affected at values less than 21 minutes of arc.) (From Krebs, 1977).

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